Navigation Sensor Accuracy Requirements for Emerging Laser Radar Applications

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ABSTRACT

The paper draws attention to the emerging military capabilities of laser radar by describing state-of-technology sensor processing results for applications involving helicopter obstacle warning, automatic target identification at far range and automatic target detection and classification at close range. In all applications sensor processing requires accurate motion compensation using navigation data, the accuracy of the navigation sensor needed depending on the application and the laser radar being used. The paper analyses how navigation and sensor errors affect sensor processing results, specifies maximal velocity and angular velocity errors of the navigation system and examines to what extent an INS with low-cost micromachined gyros and accelerometers can be expected to meet these specifications.

1.0 INTRODUCTION

Eyesafe solid state lasers with pulse powers of several kilowatts and pulse rates of 10's of kilohertz have only been available since the early 90's; their military potential has only begun to be explored. Used in scanning or staring-array laser range finders (also called laser radar or ladar for short) with high resolution and high range accuracy, they provide manned and unmanned military vehicles with previously unattained scene understanding capabilities. Applications include helicopter obstacle warning and automatic obstacle avoidance, automatic target classification and identification at high range for gunner support applications, target detection and selection for submunition dispensing UAVs and target identification and aim point selection for guided missiles.

Algorithms for each of the above applications have been developed, tested and evaluated at the FOM, using real sensor data and realistic military scenarios. The main problem to be solved in all the above applications is the real-time automatic recognition of man-made objects in natural, outdoor scenes. If only passive or non-range sensor data is available (infrared, visual, SAR, etc.), this problem is far from being solved. However, if range imagery is available, fast, robust solutions can be obtained as follows:

1) Object/ground segmentation: This step separates arbitrary objects from the terrain surface on which they are located. It requires no object models.
2) Object classification: This step performs a shape classification of objects extracted in step 1. It calculates the class probability, position and orientation of objects given a catalogue of object class features.
3) Object identification: The final step matches a geometric surface model of the expected objects with the object range data from one or more range frames.

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The algorithms operate on 3d point sets. Hence, if the imaging sensor is on a moving platform, accurate motion compensation is required to ensure that the 3d data corresponds to the true position of the points in space. This requirement is particularly important for scanning ladars, whose relatively low data acquisition rates results in distorted image point sets unless each range measurement is accurately positioned in space using navigation data. But also staring laser radars, which illuminate the entire scene with a single laser flash, require motion compensation to facilitate registration of image sequences.

Since the full potential of 3d image understanding can only be realised if range data is combined with navigation data, we envision future laser radar sensors on manned or autonomous aerial vehicles either using the on-board navigation system or having an integrated solid-state inertial measurement unit as part of the sensor processing hardware. In both cases navigation sensor accuracy has to be compatible with the resolution of the laser sensor and with the sensor processing algorithms of the particular military application.

The paper is organised as follows. Chapter 2 summarises current work at the FOM in the fields of helicopter obstacle avoidance, target identification at high range and target detection and classification at close range, describing the laser radar sensors, sensor processing, and typical ATR results, and comparing navigation sensor accuracy requirements of the various processing algorithms. A precise analysis of how navigation and sensor errors affect sensor processing results is given in chapter 3, where the concept of distortion of a 3d data set is introduced and applied to the examples of chapter 2, to obtain specifications for velocity and angular velocity errors of the navigation system. To what extent an inertial navigation system with low-cost micromachined gyros and accelerometers can be expected to meet these specifications, will be examined in chapter 4. It turns out that while the angular rate error will remain sufficiently small, the velocity drift of an unaided INS will be too high for most applications. This does not mean that GPS updates are necessary, however, since the laser radar itself can be used for in-motion alignment of the INS, thus reducing velocity errors to acceptable levels. This is not only true for flash ladars but also for scanning systems, for which we introduce a new registration technique for correcting distorted data and calculating velocity bias and angular rate bias.

2.0 LASER RADAR APPLICATIONS

2.1 Obstacle Warning for Helicopters

Helicopter obstacle warning was one of the first military applications of an eye safe laser radar, this being the only sensor which could detect wires less than 1 cm in diameter at a range of 500 m and more. Since several fatal accidents involving helicopter wire strikes occur every year, the need for an obstacle warning display is evident, particularly for military applications: Helicopter flights near ground level at high speeds are required to avoid the threat of anti-aircraft weapons while penetrating enemy territory. During such flights, wire obstacles such as supporting cables, power lines and telephone wires are extremely dangerous, especially at night and under adverse weather conditions.

Laser radars for helicopter obstacle warning have been, and are being developed by several companies, such as Fibertek, USA, Goodrich, USA, Dornier, Germany, Marconi, Italy. These are all scanning systems having frame rates of 1-2 Hz and laser pulse rates of up to 80 kHz.

A typical range image of an obstacle warning system (in this case the Dornier OWS) is shown in fig. 1, colour coded with red near and blue far. It consists of 64 columns and 320 rows with an angular resolution of 8.7 mrad between columns and 1.7 mrad between rows. The frame rate is 2 Hz. The system contains a built-in Honeywell inertial navigation system (INS), transmitting velocity and angular flight data. The INS data is used to transform the range data into a fixed 3d coordinate system.

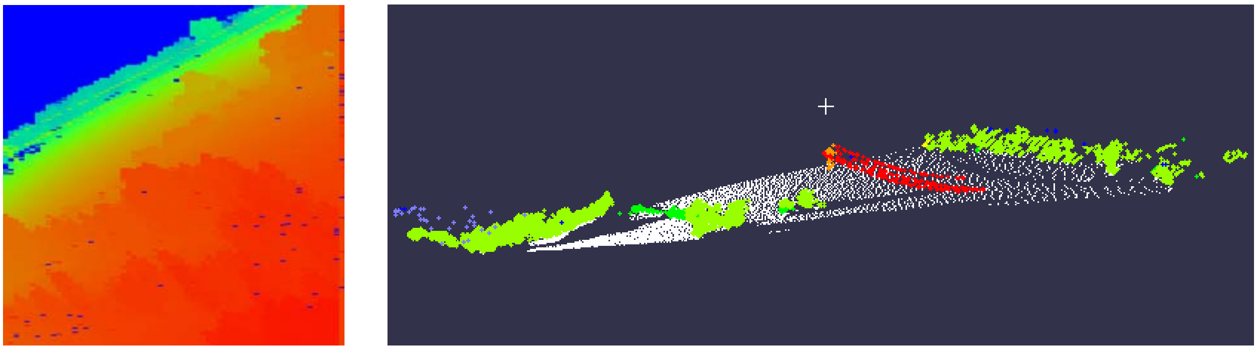
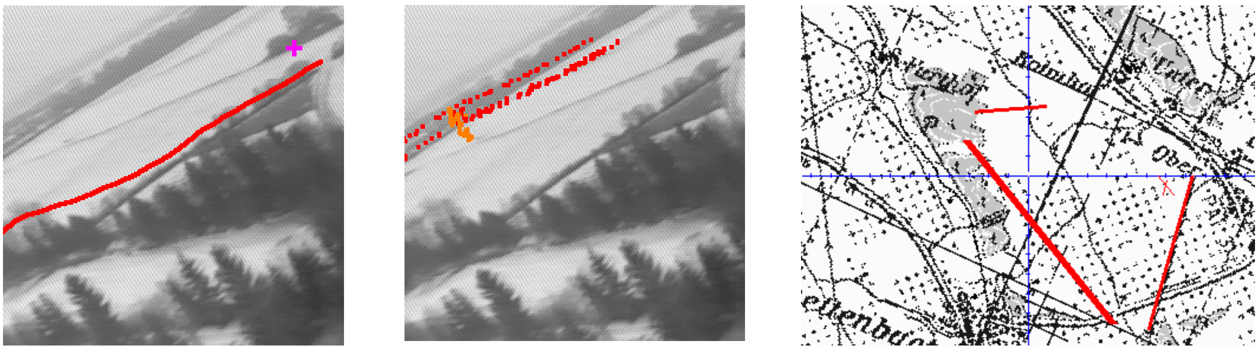


Figure 1: Colour Coded OWS Range Image and 3d Visualisation of Obstacle Classification Results.

INS error specification is determined by the type of obstacle classification algorithm applied, which in turn depends on the type of warning display the pilot requires. Three types of warning display symbologies which have been extensively tested and evaluated by pilots are shown in fig 2. The flight guidance line requires a head-up display, the obstacle image is superimposed on the pilot's sight using a helmet mounted display and the obstacle map can be displayed on a monitor. The flight guidance line is calculated in such a way that if the pilot keeps the flight vector symbol (the cross marker in fig 2a) above the line, the helicopter will clear all detected obstacles. The obstacle image (fig 2b) visualises obstacles the pilot would otherwise not be able to see, such as masts, pylons and wires. The same obstacle classes can be projected into the helicopter's digital map resulting in the obstacle map symbology of fig. 2c. The latter is primarily intended for helicopters in which no helmet mounted display is available.



a b c

Figure 2: Obstacle Warning Displays: a) Flight Guidance Line, b) Obstacle Image, c) Obstacle Map.

In order to generate the flight guidance line each range measurement must be classified as an obstacle point or a non-obstacle point. Often this is attempted by identifying non-obstacle points with isolated points (having no adjacent points in a small neighbourhood), the advantage being that the classification algorithm is simple, and, operating locally, is essentially unaffected by image distortion. The disadvantage of the algorithm is the relatively large number of classification errors. Reflections from fog, clouds, dust, birds, debris and other non-obstacles are often non-isolated, whereas returns from wires at high range or oblique angles often are isolated. To increase classification accuracy non-local operators are used, or the processing is applied to 3d points from several images. In both cases navigation data is required.

The algorithm used to generate the obstacle image warning display first differentiates terrain surface points and object points. Connected components of object points are analysed to determine whether the object contains high narrow structures such as masts, pylons, wires, which may be overseen by the pilot. Only these obstacles are included in the warning display, since the inclusion of large obstacles or even

ground points would unnecessarily clutter the pilot's sight. The results of obstacle classification are illustrated in fig 1. Since this shape analysis is fairly susceptible to image distortion, obstacle classification accuracy depends on navigation sensor accuracy.

The obstacle map requires the highest navigation sensor accuracy, since data fusion over several images occurs. In fact the algorithm uses single frame obstacle classification results to set up and continuously update an internal data base of the obstacles (for example power lines) detected during the entire flight. The warning symbology either displays the obstacles in a given vicinity of the helicopter relative to the current helicopter position, or overlays these obstacle symbols on the current display of the helicopter's digital map. In the first case an INS sensor suffices (see chapter 4), whereas in the second case the position and orientation of the helicopter relative to the map is required, which can only be provided with sufficient accuracy if GPS data is accessed.

2.2 Target Recognition at Far Range

Although target cues can readily be detected automatically in infrared images of objects at a range of several kilometres, automatic target recognition (ATR) algorithms operating on infrared data produce poor classification results. Even trained human observers have difficulties in differentiating military and non-military vehicles in IR images at a range of over 3 km.

Considerably higher target recognition probabilities can be attained using a dual laser/IR sensor system. Hot spots automatically extracted from a wide field-of-view IR image are consecutively scanned using a narrow field-of-view, high-resolution laser radar (often called a target profiler). Applying 3d ATR algorithms to the range data and conveying the classification or target identification results to the gunner of a tank or aircraft can help to reduce collateral damages, to reject decoys and to discriminate high-value targets.

No such dual sensor system exists at present, however high power laser profilers having a range of 3-5 km, angular resolutions of 100 µrad or less and a range resolution of about 30 cm are in development or have been demonstrated as prototypes. In the future such systems will most likely use flash lasers, for which no motion compensation will be required. Instead of using an m x n detector array, a linear array of m detectors may be used together with a 1d scan, each laser pulse illuminating only the linear array. This compromise achieves the required high frame rates of about 25 Hz, since only n rather than n x m laser pulses per frame are emitted, and on the other hand reduces the laser power needed for high range by a factor of n, making the ladar eye-safe. Such hybrid array/scanner ladars of course require highly accurate motion compensation.

A typical colour coded range image of such a sensor is shown in fig. 3. The ATR-algorithm first segments the image into target, ground, background, occlusions and invalid returns (fig.3b). Target returns are used to approximate target position, orientation and size (length, width, height) as illustrated in fig 3c, which shows a projection of target points (colour coded by height) into the horizontal plane. This information is used to restrict the number of models, their position and orientation in the final model-matching stage. These basic steps of segmentation, classification (including pose estimation) and model matching are combined in a new probabilistic framework, which guarantees high target recognition probabilities despite low resolution, model errors, adverse visibility conditions or partial occlusions.

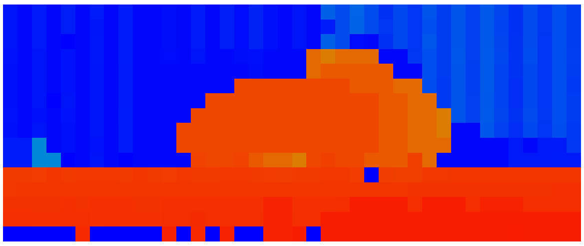


Figure 3a: Profiler Image of Vehicle at High Range.

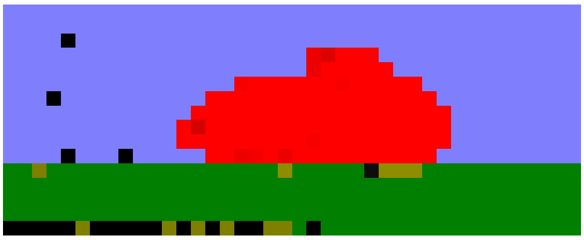


Figure 3b: Segmentation Results.

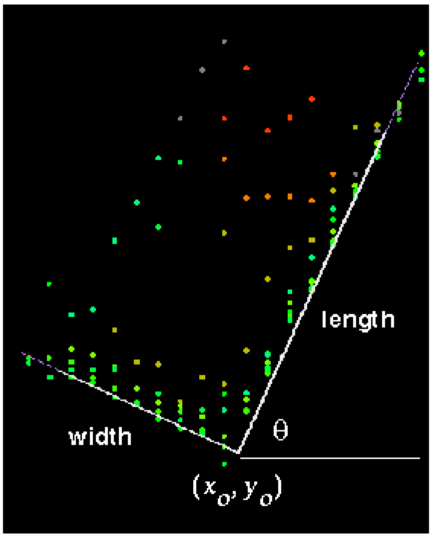


Figure 3c: Target Class and Pose Estimation.

2.3 Target Recognition at Close Range

Partially occluded, hidden, camouflaged, or cold targets may not be detectable with infrared or other passive sensors, or the number of false alarms may be unacceptably high if automatic target cueing algorithms attempt to search for such targets. Detection may be possible for the human observer at close range. However, the use of helicopters or low-flying aircraft for close-range tactical reconnaissance is extremely dangerous for the pilot, while using unmanned aerial reconnaissance vehicles together with a data link to a ground station has the disadvantage that vehicle control, for example to obtain additional target data, or to attack the target with submunition, is not feasible. As a rule, the evaluation of reconnaissance data takes much longer than data acquisition.

On the other hand, if the unmanned aircraft uses a laser radar at close range, highly reliable automatic target detection, classification and identification can be carried out in real time by the sensor processor. The relatively small number of target cues can be relayed to a ground station for target verification and combat decision, or can be further processed to automatically decide and carry out target engagement.

Algorithms for target detection at close range (up to several hundred metres) have been tested both on simulated and real sensor data.

The simulated data was generated to explore the possibility of visualising highly occluded targets, such as vehicles hidden in densely forested areas. Since only small segments of the target are visible from each viewing direction, several frames of range data need to be registered (that is, transformed into a common coordinate system) to enable automatic target cueing and visualisation for human interaction. A typical range image of two occluded vehicles is shown in fig.4a. Using 30 such images of the same scene with the simulated sensor platform flying over the targets, the results of registration and segmentation are shown in fig 4b, where ground points are green, possible target points red, and other points are not displayed, giving an unoccluded view through the foliage for the human observer.

Figure 4a: Simulated Range Image.

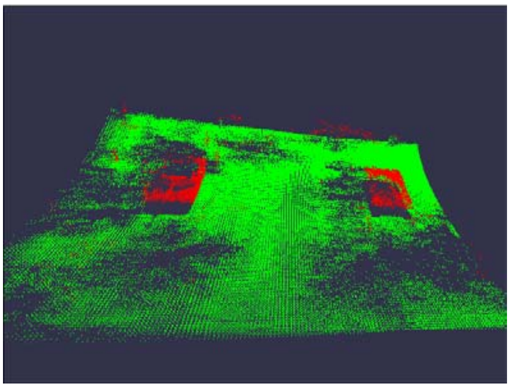


Figure 4b: Segmentation Results of 30 Images.

For this particular data set no prior navigation information was required for registration, since consecutive images overlap almost 100 per cent. In general, the smaller the overlap, the higher the accuracy required for the first pose estimate to ensure that the recursive algorithm converges to the true sensor transformation. A further need for an accurate navigation sensor arises from the relatively high computation time of the recursive algorithm. A real time application involving frame rates of over 1 Hz might apply the algorithm once a second to correct navigation sensor bias, but use the high short term accuracy of the IMU for motion compensation of intermediate frames.

Sensor development for the above application is currently being pursued in the USA (JIGSAW project).

Real data for testing and developing algorithms for target detection and classification at close range has been collected using a line scanning laser (developed by Dornier and TopoSys) operated from a low-flying aircraft. Scan direction is perpendicular to flight direction and pointing forward at a depression angle of about 45 deg. The laser pulse rate is 85 kHz and each scan line consists of 128 range values. A typical data set containing 800 scan lines (which is collected in about 1.2 s) is shown in fig. 5. Target cueing proceeds by terrain/object segmentation as above, followed by object shape classification to distinguish between vegetation and man-made objects and to find vehicle candidates (fig. 6).

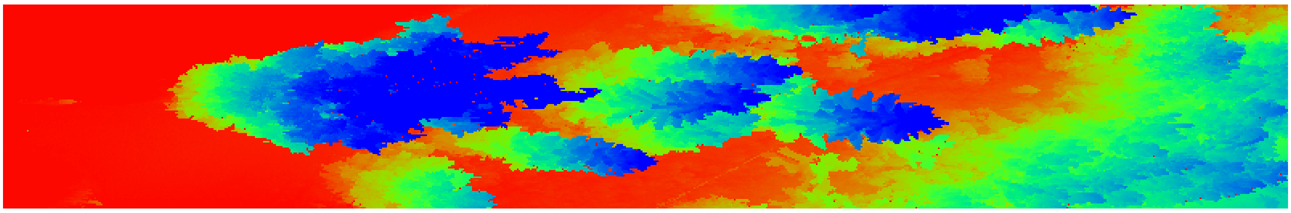


Figure 5: Toposys Range Data (red low, blue high) of 45 deg Down-Looking Laser Line Scanner.

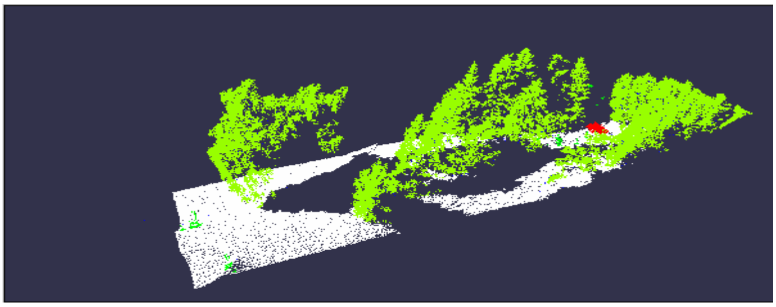


Figure 6: Terrain/Object Segmentation and Target Cueing Results.

Although data collection by line scanning is efficient, no point in the scene being measured twice, it has the disadvantage that no data registration is possible. For this reason an INS alone will not meet the accuracy requirements of the data processing algorithms, as explained below, but must be augmented by GPS data.

3.0 NAVIGATION ACCURACY REQUIREMENTS

Unlike applications of midcourse guidance or sensor pointing, the above laser radar applications essentially require no position and orientation information from the navigation sensor. Indeed, finding the position and orientation of objects is part of automatic object recognition, and can be carried out in an arbitrary coordinate system. To put it another way, the error influencing the above ATR-algorithms is not the difference between the measured and the true position of the data points (which will be large if the sensor position or orientation error is large), but the distortion of the measured data set. Distortion may be defined as the RMS position error modulo rotation and translation, more precisely, if the i^{th} data point has measured position $\overline{p}_i$ and true position p_i, the distortion of the data set is

$$\min_{R,\,T}\sqrt{\frac{1}{n}\sum_i\left(R\overline{p}_i+T-p\right)^2}$$

where the sum is taken over the n points of the data set and the minimum is taken over all rotations and translations. The data sets involved in the above definition are the objects or object parts which the algorithm attempts to classify or identify. Given the maximal distortion of the objects which the recognition algorithm can handle, we can specify accuracy requirements of the navigation and imaging sensors.

Suppose $\Delta t = t_1 - t_0$ is the time taken to collect such a data set. This time interval may be a fraction of the frame time if small objects within the range image are classified (for example isolated points or wire segments in obstacle classification), it will correspond to the frame time if the object takes up the entire field of view (e.g. single frame target recognition at high range) or will be several frame times, if the object is recognised or visualised using several range images (e.g. jigsaw-type applications or obstacle map warning displays).

Distortion depends on navigation and imaging sensor errors. The velocity error of a navigation system increases with time, while the angular rate error can be considered constant. Let δv denote the maximal velocity error during the above interval and $\delta\omega$ the angular rate error. The ladar sensor error will be denoted $\delta s = (\delta r, \delta a, \delta e)$, where δr is the range error, δa the azimuth error and δe the elevation error. Let q_i denote the sensor coordinates of the ith data point. Choosing an initial rotation and translation such that the position and orientation error of the navigation sensor at time t_0 equals 0, the distortion of the data set may be approximated by

$$\sqrt{\frac{1}{n}\sum_i\left(\delta p_i\right)^2}\text{, where } \delta p_i = Aq_i\Delta t + \delta v\Delta t + J\delta s$$

A being the angular rate matrix, and J being the Jacobian matrix of the spherical transformation. Simplifications occur if the diameter of the data set can be considered small relative to its range. In this case each q can be approximated as (r, ra, re) for small azimuth and elevation angles a and e, and

$$Aq\Delta t + \delta v\Delta t = r\Delta t\begin{pmatrix}-a\delta\omega_z + e\delta\omega_y\\ \delta\omega_z - e\delta\omega_x\\ -\delta\omega_y + a\delta\omega_x\end{pmatrix} + \Delta t\begin{pmatrix}\delta v_x\\ \delta v_y\\ \delta v_z\end{pmatrix}, \qquad J\delta s = r\begin{pmatrix}-a\delta a - e\delta e\\ \delta a - ea\delta e\\ \delta e\end{pmatrix} + \begin{pmatrix}\delta r\\ a\delta r\\ e\delta r\end{pmatrix}$$

the first factor being the contribution of the navigation error to distortion, the second factor being the contribution of the imaging sensor. A comparison of these two factors is useful, when imaging sensor resolution is given and we need to specify the accuracy of a compatible navigation sensor: distortion due to the navigation errors should negligible compared to (or maximally of the same order of magnitude as) distortion due to imaging errors. As a first approximation, this will be the case if the navigation translation error during object acquisition, $\delta v \Delta t$, is of the same magnitude as the range error, δr, and the navigation rotation error during object acquisition, $\delta\omega\Delta t$, is of the same magnitude as the angular resolution of the imaging sensor, $(\delta a, \delta e)$. In the following section this rule of thumb will be applied to the sensors and algorithms described in chapter 2.

3.1 Examples

Laser radar used for obstacle warning typically has an angular resolution of 2 mrad, a range error of 10 cm, and a frame rate of 2 Hz. Generating the flight guidance line merely requires the analysis of locally defined structures, which are scanned within a few hundredths of a second. Taking Δt as 0.1 s, we require angular rate errors smaller than 20 mrad/s and velocity errors less than 1 m/s. If features from several frames are used (to increase classification accuracy), Δt is of the order of several seconds, and we require $\delta\omega$ < 1 mrad/s and δv < 5 cm/s, approximately. Generating the obstacle image symbology requires $\delta\omega$ < 4 mrad/s and δv < 20 cm/s, since the objects analysed typically cover the entire frame, whereas for the obstacle map warning display, which combines the results from several frames, navigation accuracy should be about 10 times higher.

Laser radar for far-range object recognition typically has an angular resolution > 50 micro-radians, a range resolution of 20 cm and a frame time of 0.1 s, which we may take as Δt. Hence we require $\delta\omega$ < 0.5 mrad/s and δv < 2 m/s.

Laser line scanners for close-range reconnaissance applications, may have range errors < 10 cm, angular resolutions of a few mrad and a frame rate of about 500 scan lines per second. Angular resolution in flight direction depends on aircraft height and velocity, for example if the velocity is 100 m/s, scan line separation on the ground is 20 cm, corresponding to an angular resolution of 2 mrad if the range to ground is 100m. Data acquisition of a military vehicle would be completed in about 0.1 s. Hence the angular rate error of the navigation sensor should be less than 20 mrad/s and the velocity error less than 1 m/s.

For JIGSAW-type applications, possibly hundreds of images of a scene need to be combined. However, flash ladars can be expected to have frame rates of 100 to 1000 Hz, hence data acquisition time will be relatively short, say Δt = 1 s. Since the size of focal plane arrays is will be well under 500 x 500 pixels within the next decade, and since a rather large field of view (at least 50 x 50 deg) is required, angular resolution of the sensor will probably not be higher than 1 mrad, whereas range resolution will be limited to about 10 cm due to the primitive nature of integrated circuit timing electronics. Hence navigation sensors with angular rate errors < 1 mrad/s and angular velocity errors < 10 cm/s should suffice.

4.0 INS ERROR ANALYSIS

In the following sections we shall examine under what conditions an inertial navigation system with low-cost micromachined gyros and accelerometers can be expected to meet the above accuracy requirements.

4.1 IMU Errors

An inertial measurement unit (IMU) consists of 2 or 3 gyroscopes, measuring rotation rates about three perpendicular axes, and 3 accelerometers oriented along these axes. In the past, increasingly accurate rotating, fiber optic and ring laser gyros have been used, the present trend is towards small, low-cost

micromachined angular rate sensors of medium accuracy such as Coriolis vibratory gyros. Low-cost, reliable micromachined accelerometers have been available for several years.

Gyroscope error sources include:

- Random noise: These are uncorrelated, zero mean errors of the angular rate measurement. Integrating random noise over time results in angle random walk, whose variance is linearly proportional to elapsed time. The random noise error magnitude is usually expressed as the square root of this proportionality factor. Typical values for medium accuracy gyros are 0.1 to 1 deg/√hr.
- Bias is the expected angular rate measurement when the true angular rate is 0. It depends mainly on temperature and acceleration (for mechanical gyros), which may be measured, but calibration errors remain. Typical values for solid state gyros are 0.1 to 1 deg/hr.
- Scale factor error: Gyro output is only approximately linear with angular rate, the functional dependence varying with temperature. Residual calibration errors result in scale factor errors of 0.01% to 0.1% for low-cost gyros.

Typical error magnitudes for medium accuracy accelerometers are 0.01 to 0.1 m/s/√hr random walk, 0.1 mg to 1 mg (= 9.81×10^{-3} m/s^2) bias, and 0.01% to 0.1% scale factor error.

4.2 INS Errors

An Inertial Navigation System (INS) consists of an IMU together with a navigation and alignment processor. Whereas the IMU senses acceleration and angular rate in an inertial frame of reference, an INS is designed to navigate on the earth. Hence it must subtract the earth's gravitational, centripetal, and Coriolis acceleration from the accelerometer output to obtain the INS's acceleration with respect to the earth. It must also subtract the earth's rotation rate from the gyro output to obtain the INS's angular rate with respect to the earth. The INS then integrates the corrected acceleration and angular rates to obtain changes in velocity, position, and orientation with respect to the earth's surface.

In order to correct for the earth's acceleration and angular rate, the directions down and North must be determined in the IMU coordinate system. The INS calculates tilt and heading during ground alignment (where IMU velocity is known to be 0) and possibly during flight, if external velocity information (such as GPS, Doppler velocity or image registration data) is available.

If no airborne alignment occurs, the heading and tilt error will increase approximately linearly with time mainly due to gyro bias. Hence errors in the corrected angular rate and acceleration will also increase with time.

The error in corrected angular rate is bounded by the earth's angular rate of 15 deg/hr plus the gyro error of about 1 deg/hr. This is less that 0.08 mrad/s, which meets the angular rate specifications of chapter 3.1.

The error in corrected velocity will at first increase approximately with the square of time, at steady state however it will oscillate about a constant velocity bias with a period of 84 minutes. These are the Schuler oscillations, which result when the INS attempts to correct tilt using an erroneous aircraft velocity. The tilt error couples gravity into the horizontal accelerometers, resulting in an acceleration error in the direction *opposite* to the initial velocity error; the computed velocity will eventually reverse. The INS is in fact behaving like a pendulum whose centre of rotation is the centre of the earth.

As a rule of thumb the long-term average velocity error is about 30 m/s per deg/hr of gyro bias, for example 3 m/s for a medium accuracy gyro with a bias of 0.1 deg/hr, which does not satisfy the velocity accuracy requirements of chapter 3.1, unless (i) the applications are restricted to short flight times, or (ii) expensive ring laser gyros are used, or (iii) external velocity information is provided during flight. We shall examine the third possibility in the next section.

4.3 INS In-Motion Alignment

If GPS data is accessed, a Kalman filter may be used to continuously estimate position, velocity and alignment errors from both the IMU and GPS data and compute INS resets. This closed-loop error control, often referred to as in-motion alignment or INS air-start can limit the INS velocity error to 5 cm/s, even if only low accuracy C/A data and a medium accuracy IMU is available. This would satisfy the accuracy requirements for the applications discussed above.

Sensor velocity and angular velocity with respect to the earth can be measured directly by registering consecutive range images. As mentioned in chapter 2.3, registration requires an initial estimate of the relative rotation and translation of two image data sets in order to ensure convergence of the iterative procedure to the true transformation. If a scanning laser radar is used, the image data sets will be distorted, so that in general no rotation and translation exists transforming the data set of a range image into that of its successor image.

This is illustrated in fig 7, where a velocity bias of 20 m/s causes the mast to appear tilted forward in one image, where the mirror for the elevation scan angle moves up, and backward in the next image, where the scan is downwards. In this case registration does not involve finding a rotation and translation transforming one data set into another, but finding a constant velocity and angular rate bias which will generate the observed distortions. An iterative procedure solving this problem has been developed and tested at the FOM, having good convergence properties, even for poor initial values. For example, using an initial estimate of 0 velocity bias, the convergence of the data sets of fig 7 is shown in fig 8, where iterative corrections of distortion are shown by colour coding from red to blue. After 10 iterations the distortion error corresponds to sensor errors (fig. 9) as does the error in the calculated velocity bias.

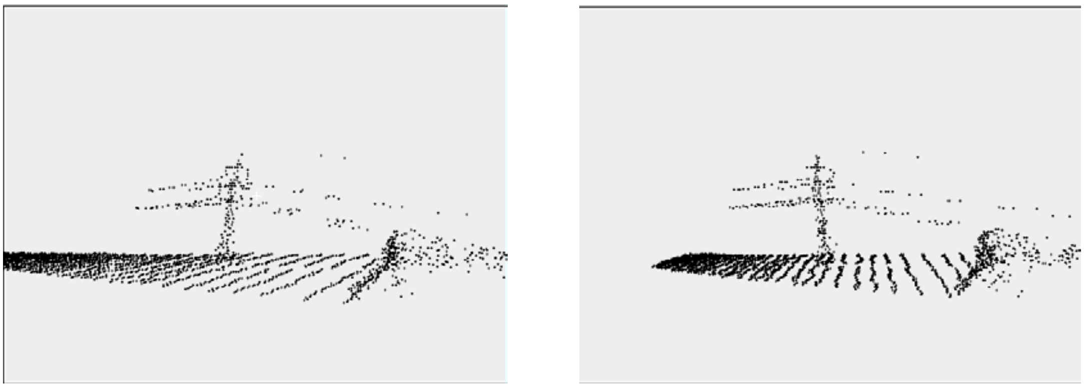


Figure 7: Consecutive Frames of a Scanning Laser Radar. INS Velocity Bias Results in Data Distortion.

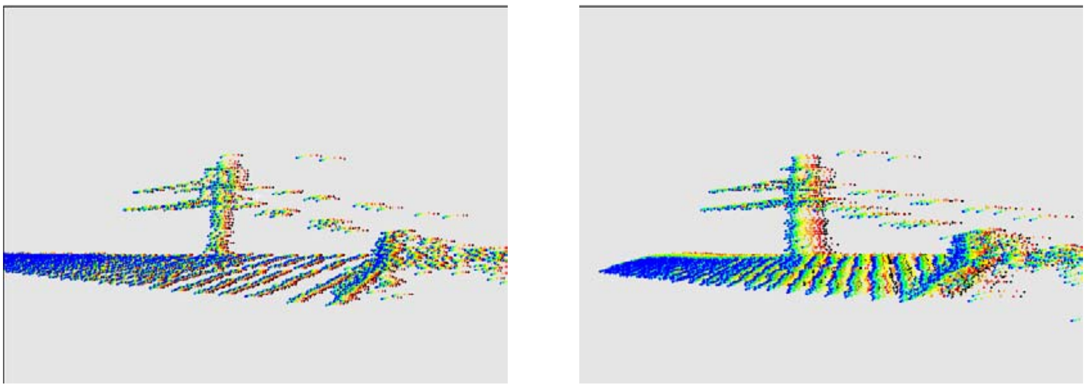


Figure 8: An Iterative Procedure Corrects Distortion and Calculates Velocity and Angular Rate Bias.

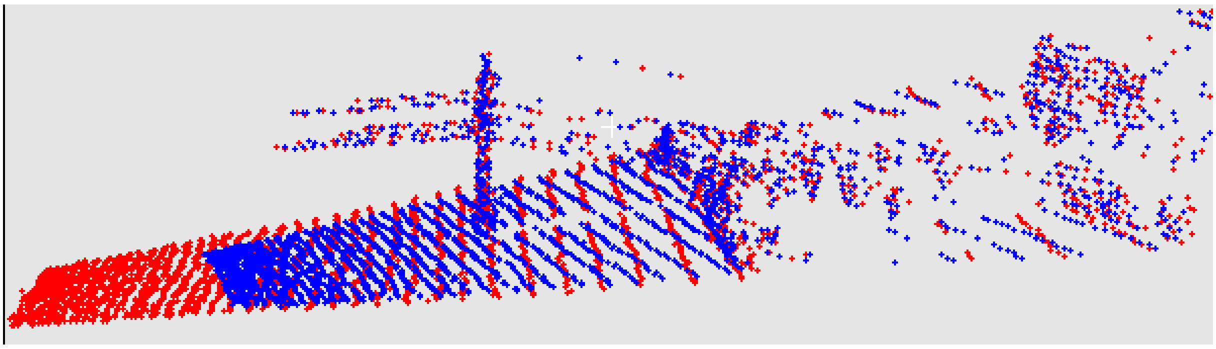


Figure 9: Overlapping Data Sets of Figure 7 after Registration.

Hence, even for scanning systems image registration can be used to measure velocity and angular velocity and to perform in-motion alignment of the INS. This not only results in reduced velocity errors which meet our specifications, but also provides increased accuracy for INS position and orientation outputs, without the use of GPS.

5.0 CONCLUSION AND OUTLOOK

The results described in this paper suggest the following thesis: laser radar and INS are necessary and sufficient sensors for a fully autonomous aerial combat vehicle, performing navigation, obstacle avoidance, target detection, target identification, and target engagement.

Laser radar will most likely be the only sensor able to perform reliable automatic object recognition within the 21st century[1], the reason being that target modelling involves only surface geometry, which is directly measured with a range sensor, whereas target modelling for passive sensors also involves target illumination, reflectivity and (in the case of IR) temperature distribution. An INS is necessary, since the points in space measured by ladar must be positioned in a common coordinate system to enable data interpretation. In the paper we have shown that even a medium accuracy INS will suffice for laser radar obstacle avoidance and target recognition, provided the ladar itself continuously updates the INS. Errors in INS position and orientation will of course grow with the square root of time despite this update. We contend, however, that for truly autonomous applications no precise position and orientation information is required.

Both laser radar and INS sensors are currently undergoing rapid technological development. We may expect the availability of a low-cost, compact, highly accurate ladar/INS system within the next few decades. Sensor processing will subsequently be pursued commercially beginning with basic system functions such as INS/ladar in-motion alignment and automatic 3d construction of point-set models to be used in object recognition, followed by various commercial applications of automatic object recognition from moving sensors. In the field of military applications, the ensuing conviction, that machine interpretation of 3d data is faster and more reliable than human interpretation of such data[2], will shift the emphasis from obstacle warning and object visualisation to autonomous terrain following, obstacle avoidance and target recognition using laser radar. Once system dependability for these basic functions is verified, in particular if target recognition probability is sufficiently high, the decision to attack or not to attack a target will not require human interaction, on the contrary, the machine decision can be expected to result in fewer air strikes against allied or civilian targets.

[1] This prediction appears controversial until one critically evaluates progress in object recognition for passive sensors during the last 30 years.

[2] For example, machine interpretation of 3d data can exploit the absolute size of objects and object parts. This information cannot be directly accessed by the human interpreter. Even if the information is presented symbolically, it cannot be processed efficiently by human vision.

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